Aging of Kraft Paper Insulation in Natural Ester Dielectric Fluid

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Abstract— **The aging behavior of transformer insulation Kraft paper aged in a natural ester oil, recently developed from palm kernel oil, is compared to the behavior of paper samples aged in mineral insulating oil. This study aimed to investigate the effect of the natural ester oil on the aging of cellulose insulation paper if used as an alternative insulating fluid in transformers. Thermally upgraded insulation paper was aged in both insulating fluids together with strips of galvanized steel, copper and aluminium to represent the transformer, under nitrogen pressure in a sealed mild steel pressure vessel for 150 degC for 28, 56, and 84 days. The degradation after aging was assessed using tensile strength and breakdown strength measurements of the paper. The paper samples impregnated with natural ester fluid exhibited similar behavior before and after aging, with an approximately 5% reduction in tensile strength after 28 days of ageing. Two sets of response were obtained for paper samples aged in mineral insulating oil under the same ageing conditions; the paper closer to the copper strips had a faster degradation rate (~35% reduction). The natural ester fluid retarded the aging of the Kraft paper. The characteristic breakdown strength of natural ester impregnated paper was found to be, on the average, 42% better than that of mineral oil impregnated paper.**

Keywords—ester fluid; insulation paper; thermal aging; tensile strength; breakdown strength

I. INTRODUCTION

Mineral-based insulation oil has performed well over the years. However, in a situation where there is accidental leakage in a transformer, the oil could constitute an environmental hazard because it is toxic and non-biodegradable. This has shifted attention towards bio-based insulating materials that are sustainable and biodegradable, and hence mitigate environmental issues. Recent publications have demonstrated the practicability of natural ester fluids as a viable alternative insulation fluid. Natural ester fluid in addition prolonged the life of the paper insulation. The strength of a dried sheet of insulation paper is dependent on the condition and strength of the fibres of which it is made and the hydrogen bonding between the cellulose molecules [1]. Voids are present within the structure of the cellulose insulation when it is dried due to space between the fibres. Impregnation of the insulating paper with oil fills the voids. This increases the electrical strength of the composite material as the oil and paper shares the applied electrical stress [2] and prevents partial discharge in the voids. Ageing leads to deterioration of the composite insulation system. This may in turn lead to decrease in the electrical and mechanical strength of the system. McShane *et al* at Cooper Power System reports that thermally upgraded paper in natural ester possesses slower ageing rate compared with when immersed in mineral oil [3]. Although the existing bio-based transformer fluid has excellent key properties, the high viscosity (33-45 cSt at 40˚C) compared to the viscosity (9.2 cSt at 40˚C) of conventional transformer oil, and its poor thermo-oxidative stability is a drawback [4,5]. A newly developed palm kernel oil alkyl ester fluid (PKOAE) with low viscosity and high thermo-oxidative stability has the potential of overcoming the drawbacks of the commercially available natural ester fluids [6]. Aging rates of insulation paper in practical amount of time was determined in the newly developed insulating fluid using accelerated aging system. A sealed systems best simulates real aging in modern sealed transformers Cooper power system accelerated aging system was adapted in the aging study. The most significant characteristics used to assess transformer aging are mechanical and electrical strength of the paper insulation.

II. EXPERIMENTAL

400 ml each of Nynas 10GBN mineral oil and PKOAE was degassed and dried in an oven at 85˚C for 2 hours. It was allowed to cool to ambient temperature and transferred to the ageing vessel. The thermally upgraded insulating paper was vacuum dried in oven at 85˚C for 24 hours. The ageing vessel containing the oil sample, 33 g of 0.255 mm thermally upgraded paper, 150 cm^2 galvanized steel strip, 112.8 cm^2 copper strip, and 150 cm^2 aluminium strip, was placed in vacuum oven for 30 minutes at ambient temperature following the Cooper Power System ageing setup [3]. The galvanized steel represents the core of a transformer, while the copper and aluminium strip represents the conducting coils. The vessel was sealed with the lid at ambient temperature and placed in the ageing oven (Fig. 1). The air inside was purged out and vessel sealed with nitrogen at ambient temperature and pressure of 400 kPa. The vessel was thermally aged at 150˚C and pressure of 600 kPa for 3 months. Samples of aged cellulose papers were taking out of the vessel for analysis. Samples; EIP00D, EIP28D, EIP56D, and EIP84D are samples

of ester-paper after 0 day, 28 days, 56 days, and 84 days of ageing respectively, and MIP00D, MIP28D, MIP56D, and MIP84D are samples of mineral oil-paper after 0 day, 28 days, 56 days, and 84 days of ageing respectively.

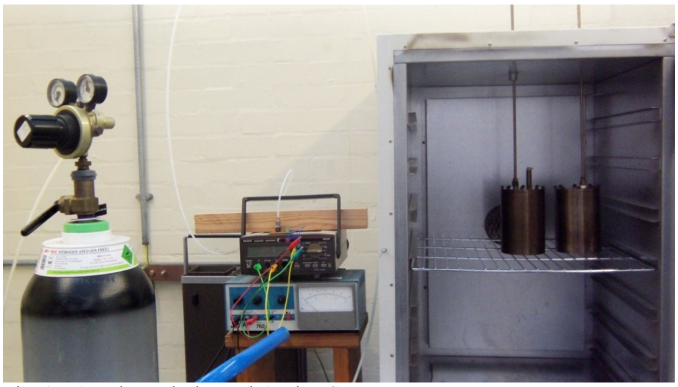

Fig. 1. Accelerated Thermal Ageing Setup

III. Results

The tensile strength of the impregnated paper samples was determined using an Instron 3343 Single Column Testing System. The instrument has force capacity of 500 N. The tensile specimens were prepared by cutting the paper samples of 0.25 mm in thickness into the appropriate "dog bone" shape. It has two shoulders and a gauge section in between. The gauge section of each specimen has length and width of 30 mm and 4 mm respectively. Five specimens were prepared from each sample. Each specimen was properly positioned in the test machine and the shoulders of the samples were firmly gripped by the upper and lower tensile grips of the test machine. Tension was applied on the specimen till deformation and failure occurred within the gauge section. The tensile stress was analysed using Bluehill 2 testing software. The result was in good agreement with previously published work [3].

TABLE I. Aging Parameters of Paper Sample

Samples	State	Tensile strength [MPa]	Ageing factor	Characteristic breakdown strength [kV/mm]
MIP00D	New	99	0%	54
MIP28D	Aged for 28 days	38	63%	55
MIP56D	Aged for 56 days	34	65%	55
MIP84D	Aged for 84 days	35	65%	54
EIP00D	New	111	0%	78
EIP28D	Aged for 28 days	105	5%	78
EIP56D	Aged for 56 days	100	10%	75
EIP84D	Aged for 84 days	99	11%	76

The breakdown strength of the paper samples was performed using breakdown test cell containing stainless steel ball electrodes of diameter 25 mm as electrodes. Paper samples of diameter 25 mm were sandwiched between the sphere electrodes in the test cell containing oil. Breakdown was performed on 6 specimens of each sample. The breakdown data was analysed using the Weibull distribution function. The results of the ageing experiment at 150°C are summarized in Table I. The tensile strength and breakdown results as shown on that table clearly show the slow ageing rate of Kraft papers aged in ester fluid.

A. *Tensile Strength*

The tensile strength result of the thermally upgraded paper samples immersed in mineral oil and PKOAE after undergoing accelerated thermal ageing is shown in figure 2. The paper layers aged in PKOAE exhibited approximately 5% reduction in tensile strength during the 28 days ageing period. The paper layers closer to the metal plates in the aging with mineral oil were found to have a significant faster degradation rate. The tensile strength of samples closer to the copper plates after ageing for 28 days dropped to about 38% of the tensile strength of the unaged sample. At the end of 84 days ageing time, paper aged in ester fluid has 11% reduction in tensile strength and those aged in mineral oil dropped to about 35% of the original tensile strength of the unaged oil-paper.

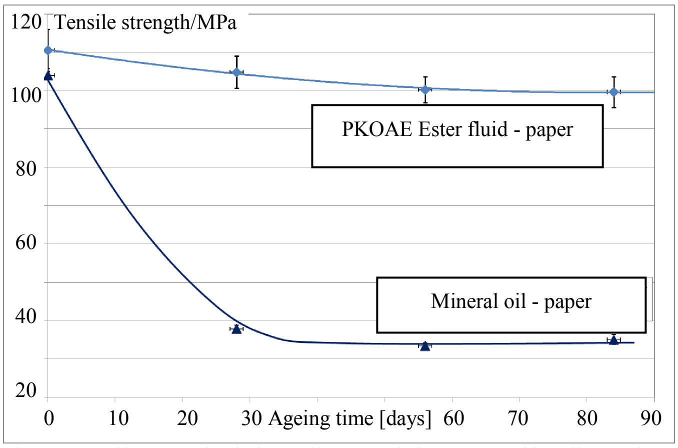

Fig. 2. Tensile Strength of Thermally Upgraded Paper Aged in Oil Samples

B. *Breakdown Strengths*

Figure 3 shows the Weibull plot of AC breakdown field data of dried and degassed paper, unaged impregnated mineral oil-paper, and unaged impregnated PKOAE-paper samples. Table II shows the Weibull parameters the dried paper sample, and different aged paper samples in both ester fluid and mineral oil. It can be observed from the Table II that characteristic breakdown field strength of PKOAE impregnated paper is much higher compared with mineral oil impregnated paper. The breakdown field of PKOAE-paper system is on the average, 42% higher than mineral oil-paper system. The characteristic breakdown strength and the shape parameters of the paper improved with impregnation. The breakdown field of the impregnated paper samples has narrow distribution as indicated by the high values for the fitted shape parameter, β. The variation in the dispersion of the breakdown data of the samples may be linked to inhomogeneous ageing of the samples.

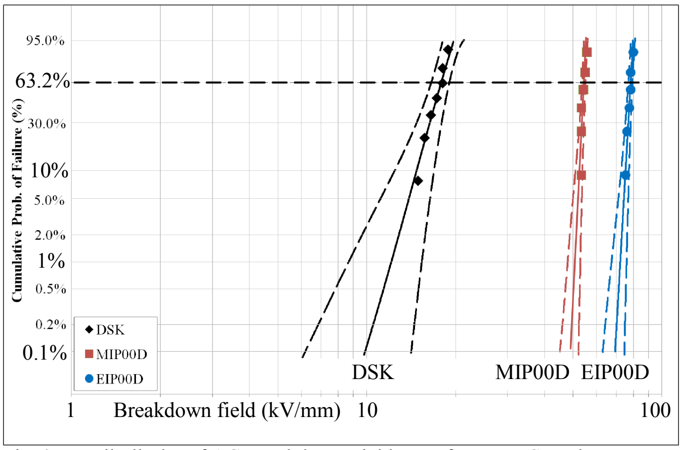

Fig. 3. Weibull Plot of AC Breakdown Field Data for Paper Sample

TABLE II. WEIBULL PARAMETERS OF AC BREAKDOWN FILED DATA FOR PAPER SAMPLES

Samples	***N***	***Characteristic value, α* (kV/mm)**	***95% Conf. Bound for α (kV/mm)***	***Shape parameter, β***	***95% Conf. Bound for β***
DKP	7	43	41.96 – 43.60	28.85	19.25 – 48.32
MIP00D	6	54	53.68 – 54.97	65.94	37.54 – 158.18
MIP28D	6	55	53.65 – 57.26	24.07	13.71 – 57.76
MIP56D	6	54	52.91 – 55.65	31.08	17.70 – 74.56
MIP84D	6	54	53.51 – 55.59	43..08	24.53 – 45.02
EIP00D	6	78	77.14 – 79.29	57.09	32.51 – 136.96
EIP28D	6	78	75.62 – 79.64	30.24	17.22 – 72.53
EIP56D	6	75	74.33 – 75.89	75.39	42.93 – 180.86
EIP84D	6	76	74.74 – 78.17	34.86	19.43 – 83.64

IV. DISCUSSIONS

Ageing of paper insulation involves chemical reactions such as pyrolysis, oxidation and hydrolysis. These mechanisms are accelerated at elevated temperatures. Under nitrogen and 150˚C, oxidation of furan degradation products (2-furfuraldehyde) of the cellulose by oxygen should not occur [7]. Since the system was aged in the absence of air, the most probable ageing mechanism is charring of the paper fibre due to thermal stress to produce solid residue, water, CO_2, CO and H_2. The water content in the system increases over time as the ageing progresses. However, the available water in the system may attack the oxygen that bridged the monomers to form two hydroxyl ions attached to each monomer. This causes scission of the inter-monomer bonds and eventual degradation of the material. The number-average degree of polymerisation (DP) is the ratio between the number of monomers and the number of chains of all lengths. Degradation led to decrease in the DP and the mechanical strength of the paper and hence a reduction in its tensile strength [8]. The presence of copper in the ageing system did not seem to have significant influence on the ageing process of PKOAE-paper system. But the presence of copper in the mineral oil-paper system acts as degradation catalyst in the system. This led to thermo-oxidative decomposition of the hydrocarbon compound, producing acidic residues as by-product [7]. This residue can accelerate the ageing of cellulose in mineral oil as observed from the Table II . The effect of the oil degradation products on the cellulose paper may have been more within the vicinity of the copper plate due to the formation of copper sulphide. This may have caused the faster degradation of paper samples closer to the copper plates.

This result is in agreement with McShane report [9] on ageing behaviour of Kraft paper in FR3 ester insulating fluid. The results show that the greater affinity of natural ester fluid for water, combined with hydrolysis, caused water to move from the Kraft paper insulation into the natural ester fluid in larger quantities than in conventional transformer oil. This cumulative equilibrium shift of water effectively dries the paper and reduces ageing due to thermo-hydrolytic degradation. Water is consumed by hydrolysis of the natural ester, producing free fatty acids. During accelerated ageing at elevated temperatures, this may react with the cellulose backbone via transesterification protecting the cellulose from hydrolysis [10].

TABLE III. TABLE STYLES

Materials	Condition	Ageing rate
Mineral oil-paper	Aged for 84 days at 150°C under nitrogen	65%
PKOAE-paper	Aged for 84 days at 150°C under nitrogen	11%
FR3-paper	Aged for 83 days at 150°C under nitrogen	47%

The significant increase in the breakdown strength of the oil impregnated paper samples could have resulted from the oil-paper combination sharing the applied electrical stress. Insulating paper impregnated with PKOAE fluid shows significantly higher characteristic breakdown field. This may be related to the higher breakdown strength of the ester fluid compared with the mineral oil. Although thermal ageing reduced the breakdown strength of PKAOE impregnated paper, the decrease in the characteristic breakdown strength of the paper samples after 84 days of ageing under nitrogen at 150˚C is not very significant. Comparing the breakdown strength of the ester and mineral oil impregnated paper, the electrical strength of the ester fluid impregnated paper is better than that of mineral oil impregnated paper. The breakdown strength of insulating paper impregnated with PKOAE is about 42% better compared to impregnation with mineral oil.

V. CONCLUSIONS

The result shows that cellulose paper impregnated with PKOAE fluid shows slower thermal degradation rate as compared with cellulose paper impregnated with mineral oil under similar ageing condition. PKOAE ester fluid-paper was also observed to aged slower than FR3 ester fluid-paper. The limited double bonds in the structure of PKOAE ester fluid may have influenced the ageing mechanism of the fluid and the Kraft paper. The rate of decrease in the tensile strength of PKOAE ester fluid-paper within the ageing condition is significantly lower. The PKOAE ester fluid-impregnated Kraft paper has higher characteristic breakdown strength, and there appeared to be no significant change in the value of the breakdown strength of the aged paper samples within the aging time studied. The use of the newly developed PKOAE ester fluid as alternative insulating fluid in power transformer will prolong the life of cellulose insulation of the equipment, and thereby prolonging the insulation life of the equipment.

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